

THE NATURE OF LIGHT AND COLOR

I. The Nature of Light

A. Light defined - Light is visible radiant energy emitted by an electromagnetic source.

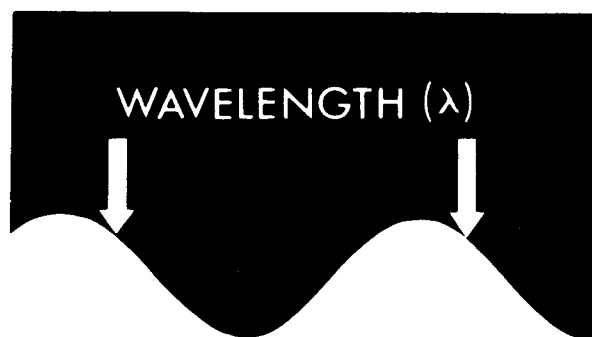
1. An electromagnetic source is one in which small, fast-moving, electrically charged particles like electrons emit electromagnetic radiant energy when forced to change speed or direction.

B. Light Movement - In a given medium, light travels in a straight line, and at a constant speed (186,000 mi. per sec. in air).

1. The energy of light is carried by tiny particles called photons.
2. As light travels, it exhibits the characteristics of wave motion.

It is these wave characteristics that give light its color.

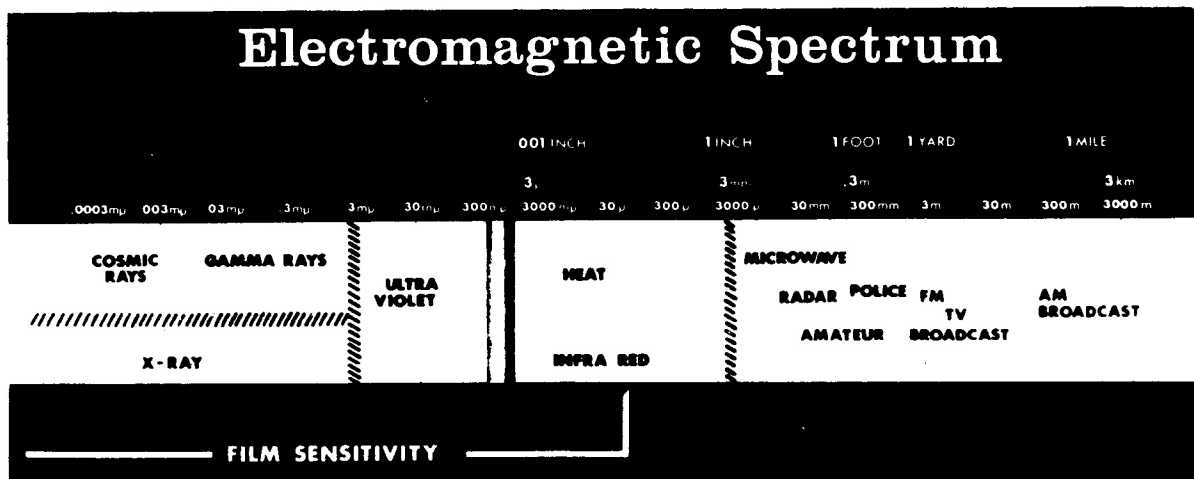
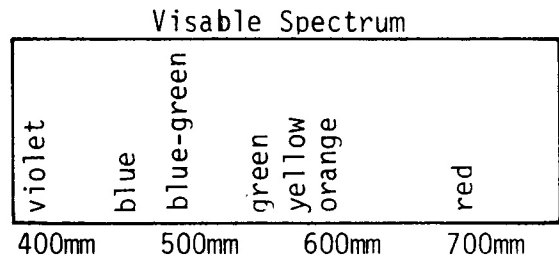
- a. Wavelength is the distance from any point on one wave to an identical point on the next wave. Frequency is the number of waves that go by in a unit of time. Velocity is frequency times wavelength.



- (1) The wavelengths of light are measured in millimicrons.
(1 millimicron = 1 billionth of a meter)
- (2) The wavelength of light extends from 400 to 700 millimicrons
(the visible spectrum). White light is a mixture of all
these wavelengths, and can be separated into component
wavelengths by passing it through a prism.
- (3) The wavelengths of infrared rays and radio waves are longer
than 700 millimicrons. The wavelengths of ultraviolet
radiation, X-rays, gamma rays, and cosmic rays are less
than 400 millimicrons.

b. The color of light is determined by its wavelength. The additive
primary colors have the following wavelengths:

- (1) blue - 450 millimicrons
- (2) green - 550 millimicrons
- (3) red - 650 millimicrons



II. The Eye and How it Sees Color

- A. Lens - collects light reflected from the subject, and forms an optical image on the eye's inner rear surface (RETINA). The brain receives the image message via nerve endings in the Retina, and interprets it; thereby making us "see."
- B. The RETINA is light-sensitive, and can be divided into three major areas.
1. RETINAL PERIPHERY (outer area) contains only RODS, nerve endings which are sensitive to all colors of the spectrum, but cannot distinguish between them; so we see white, black, or greys. The rods are extremely sensitive. However, at low levels of illumination we cannot distinguish colors.
 - a. The periphery area is used primarily to detect motion, because the images formed in this region are not sharp.
 2. The FOVEA is the central portion of the retina, and it contains only CONES, nerve endings of three types, each of which is sensitive to only one of the three primary colors (red, green, and blue).
 3. An intermediate area between the Retinal Periphery and Fovea contains both rods and cones. It senses colors, but not as sharply as the fovea region.

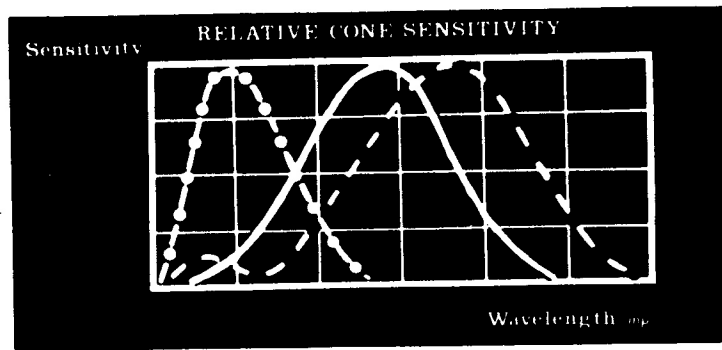
R - red sensitive cone

B - blue sensitive cone

G - green sensitive cone

0 - rods

R G B R G B R O O R O O O O O
G B R G R R G G O R B B O O O O
B R G B B G B O B O G O O O O O
G B R R G B U R G O O G O O O O



C. In any part of the FOVEA, and intermediate areas, color sensation is determined by the reflected light's relative stimulation of the three types of cones. This reflected light may be either achromatic (colorless) or chromatic (colored).

1. Achromatic light stimulates the three types of cones equally, and causes us to see neutrals (white, greys). Achromatic light is generally a mixture of equal amounts of all light wavelengths.

2. Chromatic light stimulates the three types of cones unequally, and causes us to "see" color.

a. Stimulation of only blue cones causes us to see blue; of only red cones, red; of only green cones, green.

b. Equal stimulation of only two types of cones causes us to see a subtractive primary color.

(1) red cones + green cones = yellow

(2) blue cones + red cones = magenta

(3) green cones + blue cones = cyan

III. Intrinsic Attributes of Color

A. Hue - A subject's dominant color (blue, red, green, yellow, etc.) ✓

B. Brightness - the relative total energy level of light. Brightness is both achromatic and chromatic. ✓

1. An object appears bright (and has a high brightness) because its reflected light has a high energy level.

2. An object appears dark (and has a low brightness) because its reflected light has a low energy level.

3. Black is the result of an extremely low energy level of reflected light.

C. Saturation is a measure of the relative amounts of chromatic and achromatic light in any color. The hue is very pure in saturated colors. The hue appears less pure -- appears to have gray mixed with it, in partially saturated colors.

1. Achromatic (colorless) light is totally desaturated.

2. Chromatic (colored) light may be fully saturated (spectral hues), or partially saturated (depending on the amount of achromatic light it contains).

KODAK PREPARED CHEMICALS

Condensed Information

FILM DEVELOPERS (Page I-3)

Kodak Developer D-8. A high-contrast, high-density, fast-acting developer for continuous-tone and process materials, such as Kodak Contrast Process Ortho Film and Kodak High Resolution Plates.

Kodak Developer D-11. A high-contrast developer for general use with films such as Kodak Gravure Copy, Commercial, Contrast Process Ortho, Separation Negative, Kodalith Contact, and Kodalith Royal Ortho.

Kodak Developer D-16. For motion picture positive film, such as Eastman Fine Grain Release Positive.

Kodak Developer D-19. High-contrast developer used primarily for spectroscopic films and plates, Kodak High Resolution Plates, and special films, such as Kodak Aerecon, Electrocardiograph, and Linagraph Shellburst.

Kodak Developer DK-50. A clean-working, moderately fast developer used with or without dilution for commercial and portrait films, such as Kodak Commercial, Pan Masking, Separation Negative, Royal Pan, Super-XX Pan, Portrait Panchromatic, Plus-X Pan, and RS Pan.

Kodak Replenisher DK-50R. Replenisher for Kodak Developer DK-50; increases capacity.

Kodak Developer DK-60a. A fast-acting, moderate-grain developer for general professional work with films such as Kodak Plus-X Pan, Panatomic-X, Royal Pan, Super Panchro-Press, Tri-X Pan, Super-XX Pan, and Super Speed Ortho Portrait.

Kodak Replenisher DK-60aTR. Replenisher for Kodak Developer DK-60a tank development.

Kodak Developer D-76. Full emulsion speed and maximum shadow detail with normal contrast; moderately fine grain; excellent development latitude; low fog on forced development with films such as Kodak Verichrome Pan, Plus-X Pan, Panatomic-X, and Eastman Fine Grain Release Positive.

Kodak Replenisher D-76R. Replenisher for Kodak Developer D-76.

Kodak Durafin Developer Starter. Used with Kodak Durafin Developer Replenisher for commercial photofinishing of roll films. Developer has extra high capacity and long life. Produces low density negatives for low graininess and faster printing.

Kodak Durafin Developer Replenisher. Working developer made by diluting replenisher and adding Kodak Durafin Developer Starter. One Size A Starter plus one 5-gallon size Replenisher required for each 12 gallons of working developer. Used full strength (without Starter) as replenisher.

Kodak HC-110 Developer (Liquid). A highly active developer supplied in concentrated liquid form. Designed for rapid development of most black-and-white films. Produces negatives of similar quality to those obtained with Kodak Developer D-76 but with shorter development times. Also used for processing Kodak Super-XX Pan Film separation negatives for the Dye Transfer Process.

Kodak HC-110 Developer Replenisher (Liquid). Replenisher for Kodak HC-110 Developer; increases capacity.

Kodak HRP Developer (Liquid). For Kodak Electron Image and High Resolution Plates.

Kodak Microdol-X Developer (Powder). Low graininess coupled with maximum sharpness; low sludging tendency; low fog level with films such as Verichrome Pan, Plus-X Pan, Panatomic-X, Tri-X Pan, and Infrared.

Kodak Microdol-X Liquid Developer. Same as above but ready-to-use liquid.

Kodak Microdol-X Replenisher (Powder). Replenisher for both Kodak Microdol-X Developer (Powder) and Kodak Microdol-X Liquid Developer.

Kodak Polydol Developer. For commercial and portrait work. Has exceptionally high capacity with consistent activity when replenished. Recommended for use with Kodak Portrait Panchromatic, Super Speed Ortho Portrait, Panatomic-X, Super-XX Pan, RS Pan, Super Panchro-Press, Royal Pan, Tri-X Ortho, Plus-X Pan, and Tri-X Pan Sheet Films.

Kodak Polydol Replenisher. Replenisher for Kodak Polydol Developer.

Kodak Professional Line Copy Developer. For Kodak Professional Line Copy Film.

PAPER DEVELOPERS (Page I-3)

Kodak Dektol Developer. For neutral and cold-tone images on cold-tone papers, such as Kodabromide, Kodak Medalist, Velox, Azo, Resisto, Polycontrast, and Panalure. High capacity, uniform development rate, good keeping.

Kodak Duomat Developer. For continuous or tray processing of cold-tone double-weight papers, such as Kodak Velox Unicontrast, Medalist, Polycontrast, and Azo. Requires addition of Kodak Developer Starting Solution.

Kodak Flomatic Developer. A concentrated liquid developer for continuous processing of cold-tone papers such as Kodak Velox Unicontrast. Requires use of Kodak Developer Starting Solution.

Kodak Hi-Matic Developer. For continuous processing of either single- or double-weight Kodak Velox Unicontrast and Premier Papers. Gives cold blue-black image tone. Requires use of Kodak Developer Starting Solution.

Kodak Hi-Temp Developer Additive. Added to Kodak Hi-Matic or Flomatic Developers enables processing of Kodak Velox Unicontrast Paper at 80 F and 85 F.

Kodak Selectomat Developer. For continuous or tray processing of warm-tone papers, such as Kodak PolyLure and Ektalure. Requires addition of Kodak Developer Starting Solution.

Kodak Developer Starting Solution. Required to make fresh working developer solution with Kodak Duomat, Flomatic, Hi-Matic and Selectomat Developers.

Kodak Ektaflo Developer, Type 1. For cold-tone papers, such as Kodabromide, Kodak Medalist, Velox, Azo, Resisto, Polycontrast, and Panalure. Supplied as a concentrated liquid which dilutes 1 part concentrate with 9 parts water.

Kodak Ektaflo Developer, Type 2. Noncarbonate developer for warm-tone papers, such as Kodak Ektalure, Opal, Athena, Aristo, PolyLure, and Mural. Supplied as a concentrated liquid which dilutes 1 part concentrate with 9 parts water.

Kodak Ektanol Developer. Noncarbonate developer for warm-tone papers, such as Kodak Ektalure, Opal, Athena, Aristo, PolyLure, and Mural. Minimizes stain on prints which are to be toned.

Kodak Selectol Developer. For warm-tone papers, such as Kodak Ektalure, Opal, PolyLure, Athena, and Aristo.

Kodak Selectol-Soft Developer. Used in conjunction with Kodak Selectol Developer for lower contrast on warm-tone papers.

Kodak Versatol Developer. Concentrated liquid all-purpose developer for films or papers. Diluted 1 to 3 for papers or 1 to 7 for films.

DICTIONARY OF PHOTOGRAPHIC TERMS

ADJUSTABLE CAMERA: a camera with manually adjustable distance settings, lens openings, and shutter speeds.

AUTOMATIC CAMERA: a camera with a built-in electric eye that automatically adjusts lens openings in response to the brightness of the subject. In some cameras, this automatic adjustment is also linked to the shutter-speed settings.

B-C UNIT OR B-C POWER SUPPLY: B-C stands for battery-condenser. The condenser is used in conjunction with a battery and placed into a flashholder. Maximum power is stored in the condenser for immediate use. It prolongs battery life, and assures dependable flash operation for a long period of time.

BETWEEN-THE-LENS SHUTTER: a shutter whose blades operate between two elements of the lens. Sometimes applied to an iris diaphragm whose blades operate between lens elements.

BOUNCE FLASH: light from a flash source that reaches the subject after first being reflected ("bounced") from a surface such as a ceiling or wall.

CAMERA ANGLES: various positions of camera in relation to subject. Each angle or position gives a different view or effect.

CLOSE-UP LENS: any single lens placed in front of any camera lens to permit pictures being made closer to the subject than the camera lens alone will allow.

COLOR NEGATIVE FILM: film that, when processed, becomes a color negative; used primarily to obtain color prints.

COLOR REVERSAL FILM: film that, when processed, becomes a positive color transparency; used primarily to obtain color slides.

DARKROOM: a lighttight area used primarily for processing films and papers. Also used for loading and unloading film holders and cameras.

DENSITY: the darkness of the negative (or print) and the amount of light that will pass through it; an overexposed negative is more dense than a normal or underexposed negative.

DEPTH OF FIELD: the area in sharp focus; depends upon the size of the lens opening and the distance from lens to subject.

DEPTH OF FOCUS: the range over which the film can be shifted and still have the subject in sharp focus; often used, but incorrectly, to mean depth of field.

DEVELOPER: the solution used to bring out the image on exposed film or photographic paper.

DIAPHRAGM: a device such as a perforated plate, or an iris, usually mounted between elements of the lens or right behind the lens, used to control the amount of light that will reach the film. Diaphragm openings are usually marked in f/numbers, but on simple cameras they may be marked with EV numbers or just "Bright Sun" and "Cloudy Bright." See also: "IRIS DIAPHRAGM."

ELECTRONIC FLASH: a repeatable, brilliant flash source created by an electric condenser discharging instantaneously (1/500 second or less) through the rare gas in a long-life, replaceable flash tube. The condenser recharges from a portable battery or a 110-volt power supply.

EMULSION: a thin coating of light-sensitive material, usually silver halide in gelatin, that forms the image on film and photographic papers.

ENLARGEMENT: a blowup, or print, that is larger than the negative.

EXPOSURE INDEX: a number used to indicate the amount of light needed to get a normally exposed film; it means the same as "film speed" or "ASA number."

EXPOSURE METER: an instrument with a photoelectric cell used to measure the intensity of light as an aid in selecting the exposure setting, also called a "light meter."

EXPOSURE SETTING: the lens opening (f-number) and shutter speed selected to expose the film.

FILL-IN-FLASH: light from a flash source (flashbulb or electronic flash) used on or near the camera to add to the primary light, to show better detail in the shadow areas of subjects in sunlight.

FILM SPEED: the amount of light needed to expose the film properly; it means the same as "exposure index" or "ASA number."

FILTER: a colored glass or other transparent material used over the lens for special purposes, such as making clouds photograph better.

f-NUMBER: any of the numbers used to mark the diaphragm openings on a camera. These numbers help one get the right film exposure; the numbers actually indicate the ratio of the focal length (distance from the lens to the film) to the effective diameter of the lens (diaphragm openings). For example: f/2.8, f/4, f/5.6, f/8, f/11, f/16.

FOCAL LENGTH: the distance from the lens to a point behind the lens where the light rays are focused when the light comes from a great distance; thus, the distance from the lens to the film when the lens is focused on infinity.

FOCAL PLANE: the surface (plane) on which an axial image transmitted by a lens is brought to sharpest focus; the surface occupied by the light-sensitive film or plate in a camera.

FOCAL-PLANE SHUTTER: a black curtain that moves across in front of the film and admits light through a slit; used on single-lens reflex cameras.

GUIDE NUMBERS: numbers used to determine the lens openings for making flash pictures. These numbers are found on film instruction sheets, flashbulb packages, photo guides and other publications dealing with flash photography. To find the correct lens opening, the flash-to-subject distance is divided into a specific guide number. For example, using a guide number of 80 and a distance of 10 feet, the lens opening is f/8 (80÷10=8).

GRAININESS: the mottled appearance of a photographic print, caused by the clumping of silver grains during the development of the negative. Graininess becomes more noticeable as faster films are used, as density of the negative increases, and as prints are enlarged.

HYPD: the common name for an acid hardening fixing bath that is made from sodium thiosulfate, other chemicals, and water.

IRIS DIAPHRAGM: term applied to the adjustable aperture fitted into the barrel of photographic lenses and so called because the contraction of the aperture resembles that of the iris (pupil) in the human eye. It consists of a series of thin metal tongues overlapping each other and fastened to a ring on the lens barrel, the aperture made smaller or larger by turning the ring.

LENES: in photography, the optical instrument or arrangement of light-refracting elements in a group, the whole designed to collect and distribute rays of light in the formation of an image.

LENS SPEED: the widest diaphragm openings (smallest f-numbers) at which the lens can be used, as, "an f/3.5 lens."

LIGHT METER: an instrument for measuring amount of light; the same as exposure meter.

LIGHT SOURCE: For taking pictures: natural or artificial light. For printing negatives: enlarging or printing lamp.

MULTIPLE FLASH: two or more flash

sources used to provide better lighting than is possible with a single flash source. These sources may be connected by a cord, or one or more slave units may be used.

NEGATIVE: the developed film, a reverse image of the subject.

PAN OR PANCHROMATIC: film sensitization designed to record colors in about the same relative brightnesses as the normal human eye sees them.

PARALLAX: the difference in the field of view as seen through the viewfinder and by the lens.

PICTURE COMPOSITION: the arrangement of elements (subject, foreground, background, etc.) in a picture.

POLAROID CAMERA: a camera made by the Polaroid Corporation. It uses only Polaroid black-and-white or color film, and is capable of producing a finished print directly from a door in the back of the camera shortly after an exposure is made.

POSITIVE: the opposite of a negative, thus, for example, a finished print.

RANGE FINDER: a device included on some cameras as an aid in focusing. It optically measures the distance between the camera and the object focused upon.

REFLECTORS: reflecting surfaces designed in a variety of shapes, sizes and materials. Reflectors are used to direct light in a controlled fashion to a specific area.

REFLEX CAMERA: a camera so made that the scene to be photographed is reflected by a mirror onto a glass, where it can be focused and composed in exactly the same size as the negative. With a single-lens reflex camera, the scene is viewed through the same lens that takes the picture, thus avoiding parallax; with a twin-lens reflex camera, the scene is viewed through the top lens and the picture is taken with the bottom lens.

SEMI-AUTOMATIC CAMERA: a camera with a built-in electric eye that indicates the subject brightness it "sees," generally in terms of lens openings. Usually this information is used to set the camera lens opening manually.

SHUTTER: the mechanically actuated device with a photographic lens for controlling the duration of camera exposures. Shutters may be located before, behind or within the elements of a lens. Other shutters may be adjacent to the focal plane.

SLAVE UNIT: an auxiliary flash source designed to fire simultaneously with the primary flash source; used to improve the lighting. The light surge from the primary flash (on or near the camera) triggers the slave unit.

STOP BATH: an acid rinse, usually a weak solution of acetic acid, used between the developer and the acid hardening fixing bath when developing film or paper; it stops development instantly and makes the hypo last longer.

SYNCHRONIZATION: (as applied to synchronized flash) the automatic simultaneous operation of a camera shutter with the firing of a flash source. Good synchronization means that the greatest illumination available from the flash occurs when the shutter is wide open.

TELEPHOTO LENS: a lens that creates a larger image on the film than a normal lens; a telephoto lens has a longer focal length and a smaller angle of view than a normal lens.

THIN NEGATIVE: a negative that has been underexposed or underdeveloped or both, so that it appears more transparent than a normal negative.

UNDEREXPOSURE: too little light reaching the film, producing a thin negative or an overly dark slide lacking in many or all details.

WIDE-ANGLE LENS: any lens that covers an angle of view of about 50 degrees or more.

CHAPTER 13

COLOR

13-1 Colorimetry. A modern magazine with its wealth of illustrations in color, color photography for the amateur as well as the professional, colored plastics, goods in colored packages, all testify to the increasing importance of color in our daily lives. Color has become the concern not only of the artist, but of the physicist and chemist and of the engineer and industrialist as well.

The following statement of Lord Kelvin was quoted in Chap. 1 of the first book of this series and it is appropriate to repeat it here. "I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of *science*, whatever the matter may be." We have today a science of color; color is something that can be measured and expressed in numbers. The science of color measurement is called *colorimetry*.

The word color is commonly used in several different senses. The psychologist uses the word with reference to the sensation in the consciousness of a human observer when the retina of his eye is stimulated by radiant energy. In an entirely different sense, the term is used to specify a property of an object, as, for example, when we say that the color of a book is red. The Committee on Colorimetry of the Optical Society of America has recommended the following definition: "*Color consists of the characteristics of light* other than spatial and temporal inhomogeneities; light being that aspect of radiant energy of which a human observer is aware through the visual sensations which arise from the stimulation of the retina of the eye."

The "characteristics of light" referred to in this definition are threefold. The first is *luminous flux*, which is a measure of the effectiveness of the light in evoking the sensation of brightness. The other two characteristics, which are referred to jointly as the *chromaticity* of the light, are *dominant wave length* and *purity*. Methods for determining dominant wave length and purity will be described in this chapter. The former corresponds to the attribute of *color sensation* called *hue*, the latter to the attribute called *saturation*.

13-2 Additive color mixture. Suppose that three projection lanterns, A , B , and C , are set up so as to project onto a white screen three overlapping circular patches of light, each of a different color, as in Fig. 13-1. The light from each lantern is referred to as a *component*. The regions lettered A , B , C , in Fig. 13-1, are illuminated by a single component. The regions lettered $A + B$, $B + C$, and $A + C$, are illuminated by two components, while all three components illuminate the central region lettered $A + B + C$. The light reflected from a region illuminated by more than one component is called a *color mixture*. The mixture is additive, because the reflected light is made up of the fraction of component A reflected by the screen, plus the fraction of component B reflected, plus the fraction of component C reflected.

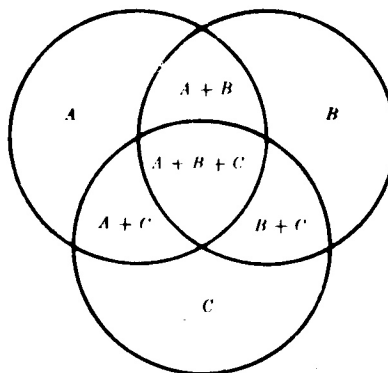


FIG. 13-1. Additive color mixtures.

It is well known that each of the mixtures differs from the others in color, as well as differing from each of the three components. Furthermore, it is not possible to detect in any mixture the colors of the components of which it is composed. In this respect the eye differs from the ear. If two notes of different pitch are struck simultaneously on a piano, the resulting sensation is not that of a single pitch intermediate between the two; but both notes can be distinguished. Our sense of hearing is analytical, while our color sense is not.

Let us now adjust the projection lanterns A , B , and C , so that all three circles coincide as in Fig. 13-2, and with a fourth lantern X project onto the screen a second circle illuminated by light of any arbitrary color. If

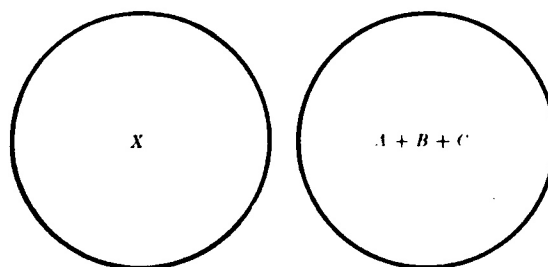


FIG. 13-2. An additive mixture of three components A , B , C , matches the color X .

lanterns *A*, *B*, and *C* are each provided with a device for controlling the quantity of luminous flux emitted (for example, a rheostat in series with the projection lamp) it is found that a wide gamut of colors at *X* can be matched by additive mixtures of the components *A*, *B*, and *C* in the proper proportions.

When used in this way, the apparatus constitutes one form of *colorimeter*. We can say that the color at *X* has been measured, in the sense that it can be specified by three numbers representing the quantities of the three components that are required for a color match.

Although a wide gamut of colors at *X* can be matched by the additive mixture of any three arbitrary components, it is not possible to match all colors. This is not because of a faulty choice of components. A second set of components, different from the first, could be combined to match some colors which the first set could not, but it would then be found that other colors, which could be matched by mixing the first set, could not be matched by the second. To extend the number of components to four or more would widen the gamut to some extent, but unless the number of components were infinite there would still be some colors for which a match could not be secured.

It is found that when a color at *X* cannot be matched by an additive mixture of three components, a color match can be secured between a mixture of the unknown and one of the components, on one hand, and a mixture of the other two components on the other. For example, a mixture of *X* and *A* might be matched by a mixture of *B* and *C*. In some cases, it may be necessary to add two of the components to the color at *X*, and match this mixture with the third component. Thus even if it is not possible to *match* the original color with but three components, it is nevertheless possible to *specify* it by stating the quantity of the component (or components) which, when added to it, will result in a match with stated amounts of the remaining components. Thus *all colors can be measured in terms of any three components*, and the results of the measurement expressed by three numbers. Quantities of any component that must be added to a given color to secure a match are considered negative.

We see, therefore, that the common belief that all colors can be matched by a mixture of three properly chosen "primary colors" is incorrect, unless the concept of "matching" is extended in the sense described above. Furthermore, there are no three unique components that *must* be used for color matching. We shall show later that red, green, and blue components permit matching the widest gamut of colors without using negative quantities of a component, and in this sense red, green, and blue, can be considered as the "primary colors."

Notice that the preceding statements are experimental facts, and are independent of any theories of color vision.

13-3 Three color mixture data for matching spectrum colors. It is not necessary actually to set up a colorimeter and match a given color, in order to know the amounts of three arbitrary components that would be required for a match. A preliminary experiment is first performed in

which one measures the amounts of the components needed to match all of the *spectrum colors*. (By a spectrum color is meant the color of a light beam comprising only a narrow range of wave lengths.) Then the amounts of the components that would be required to match any given color can be computed if the radiant flux at each wave length, in the given color, is known. The method of computation is explained in Sec. 13-4.

Fig. 13-3 shows, for one particular set of components, the amount of each required to match a spectrum color at any wave length. These components are themselves spectrum colors; a red of wave length $650\text{ m}\mu$, a green of wave length $530\text{ m}\mu$, and a blue of wave length $425\text{ m}\mu$. The ordinates of the curves give the number of lumens of each component such that an additive mixture matches 1 watt of radiant flux at the indicated wave length.

If other components had been used, a different set of curves would, of course, have been obtained. It is possible, however, by an algebraic transformation, to compute what the form of the curves would be for any other set

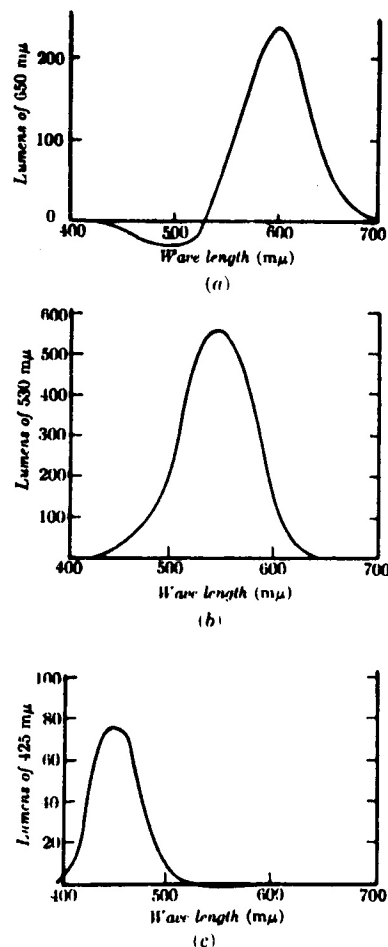


FIG. 13-3. Number of lumens of each of three monochromatic components required to match 1 watt of monochromatic radiant flux.

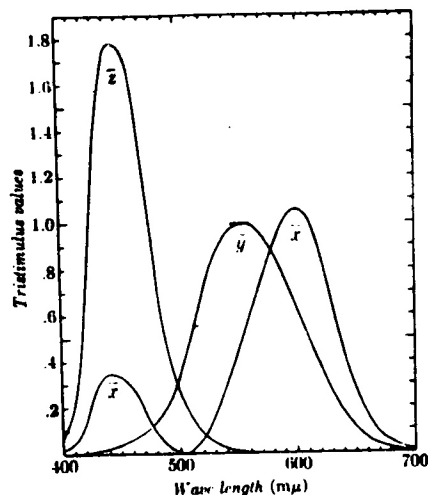


FIG. 13-4. Standard I.C.I. color mixture curves.

of components, so experiments need be performed with one set of components only.

The International Commission on Illumination, in 1931, agreed to express all color mixture data in terms of three components so chosen that the curves corresponding to those in Fig. 13-3 were everywhere above the X -axis. This avoids the use of negative numbers in computations. The standard I. C. I. components lie outside the realm of real colors¹, but this is not of importance since, as stated above, the amounts of the components required for a match can be obtained by mathematical methods without the necessity of

setting up an actual colorimeter. As long as everyone agrees to specify colors in terms of the same set of components, one set is as good as another.

The standard I. C. I. color mixture curves are given in Fig. 13-4. For convenience in computation, the ordinates are expressed in arbitrary units so that the areas under all three curves are equal. The symbols $\bar{x}$, $\bar{y}$, and $\bar{z}$ are used for the ordinates of the respective curves, and the values of $\bar{x}$, $\bar{y}$, and $\bar{z}$, at any wave length, are called the *tristimulus values* of a spectrum color of that wave length. Thus the tristimulus values of green light of wave length 500 $m\mu$ are

$$\bar{x} = 0.0049, \quad \bar{y} = 0.3230, \quad \bar{z} = 0.2720.$$

Since three numbers (the three tristimulus values) are required to specify a color, a three dimensional diagram would be needed to represent colors graphically. This difficulty is avoided by introducing three other quantities x , y , and z , defined (for spectrum colors) by the equations

$$x = \frac{\bar{x}}{\bar{x} + \bar{y} + \bar{z}}, \quad y = \frac{\bar{y}}{\bar{x} + \bar{y} + \bar{z}}, \quad z = \frac{\bar{z}}{\bar{x} + \bar{y} + \bar{z}}.$$

The quantities x , y , and z , are called *trichromatic coefficients*. Since from their definition $x + y + z = 1$, any two of these quantities are sufficient

¹ See Sec. 13-6.

to define a color. The quantities x and y are those usually chosen. Taking spectrum light of wave length $500\text{ m}\mu$ as an example, we find:

$$x = \frac{.0049}{.5999} = 0.0082, \quad y = \frac{.3230}{.5999} = 0.5384, \quad z = \frac{.2720}{.5999} = 0.4534.$$

Hence this spectrum color may be represented in a two-dimensional rectangular coordinate system by a point whose coordinates are $x = 0.0082$, $y = 0.5384$. If the same computation is made for all spectrum colors, and the results plotted, the curve shown in Fig. 13-5 is obtained. This curve is called the *spectrum locus*, and the diagram a *chromaticity diagram*.

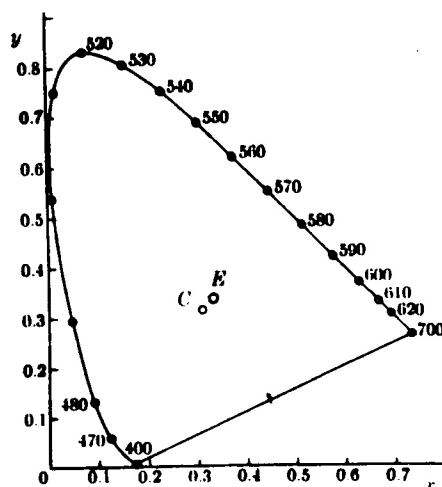


FIG. 13-5. Chromaticity diagram showing the spectrum locus and illuminants C and E .

The color names commonly associated with certain portions of the spectrum are listed below.

Designation	Wave length ($\text{m}\mu$)
Violet	Shorter than 450
Blue	450-500
Green	500-570
Yellow	570-590
Orange	590-610
Red	Longer than 610

13-4 Trichromatic coefficients of light of any color. The three tristimulus values of any sample of light are defined as the amounts of the three I. C. I. standard components which when added would match the sample. These values are denoted by X , Y , and Z , and may be computed by an

integration process. The ordinates of the curves in Fig. 13-4 represent the amounts of the I. C. I. components required to match unit quantity of radiant flux at each wave length. Let $f(\lambda)d\lambda$ be the radiant flux at wave length λ in the given sample of light. The amount of the first primary required, for this wave length range, is then

$$\bar{x}f(\lambda)d\lambda,$$

and hence the total amount for a match is

$$X = \int_0^\infty \bar{x}f(\lambda)d\lambda. \quad (13-1)$$

In the same way,

$$Y = \int_0^\infty \bar{y}f(\lambda)d\lambda, \quad Z = \int_0^\infty \bar{z}f(\lambda)d\lambda. \quad (13-2)$$

Since the curves in Fig. 13-4 cannot be expressed analytically, the integration must be performed by graphical, numerical, or mechanical methods. Instruments are available which perform the integration automatically and with sufficient precision.

Having found the X , Y , and Z tristimulus values, the trichromatic coefficients x , y , and z can be computed from the equations

$$x = \frac{X}{X + Y + Z}, \quad y = \frac{Y}{X + Y + Z}, \quad z = \frac{Z}{X + Y + Z}. \quad (13-3)$$

When the procedure above is carried out for a sample of light in which the radiant flux is the same in each wave length interval (a so-called *equal-energy* spectrum) one obtains $x = .333$, $y = .333$. The chromaticity of such a sample is represented by point E in Fig. 13-5. A standard illuminant known as *illuminant C* (see Sec. 13-6), which is a satisfactory substitute for average daylight, is plotted at point C .

Notice that the integration indicated by Eqs. (13-1) and (13-2) is of precisely the same form as that used to evaluate the luminous flux in a sample of light. (See Eq. (12-2).) A great deal of foresight was displayed by the I. C. I. in its selection of the standard I. C. I. components, when they chose the y -component so that the curve of $\bar{y}$ /vs λ , in Fig. 13-4, has exactly the same form as the standard relative luminosity curve in Fig. 12-2. The trichromatic coefficient Y is therefore directly proportional to the luminous flux in the sample.

13-5 Spectrophotometry. We see objects by means of the light they reflect. (For simplicity, the discussion will be limited for the present to opaque, nonself-luminous objects.) According to the Colorimetry Committee's definition of color, it is not strictly correct to attribute color to an object, but only to the light reflected from it. The color of the reflected light depends on the color of the incident light, and on the particular way the color is modified in the reflection process, since most objects do not reflect uniformly throughout the spectrum. Their reflectance (i.e., the fraction of incident light reflected) is a function of wave length and they are said to exhibit *selective reflection*.

The methods of measuring the reflectance of an object at each wave length constitute one branch of the science of *spectrophotometry*. The principle of one type of spectrophotometer is shown in Fig. 13-6. Light from a source *A* is dispersed by prism *B*, and a narrow range of wave lengths is isolated by slit *C*. The beam passing through the slit is divided at *D* into two beams of equal intensity by a half-silvered mirror or its equivalent. The transmitted beam strikes a standard white surface of

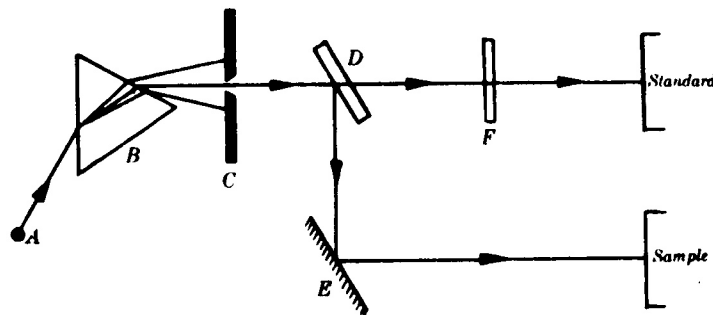


FIG. 13-6. Principle of the spectrophotometer used to measure spectral reflectance.

magnesium oxide, while the reflected beam, after reflection from mirror *E*, strikes the surface of the sample. The latter, in general, has a lower reflectance than the standard white, so it appears less bright than the standard. The quantity of light striking the standard may be reduced by a device shown schematically at *F*, until sample and standard appear equally bright. If, for example, the light incident on the standard must be reduced by 50% to secure a brightness match, the reflectance of the sample at this wave length is 50%. By repeating the measurement at other wave lengths, the complete reflectance curve of the sample may be obtained.

Fig. 13-7 is a photograph of an automatic recording photoelectric spectrophotometer developed by Professor A. C. Hardy of M. I. T. In

this instrument the standard and sample are viewed by a photoelectric cell, the amplified current from which is used to adjust the light beams until equal quantities of light are reflected from standard and sample. The reflectance curve is drawn by the instrument on a sheet of coordinate paper.

Fig. 13-8 shows six colored rectangles. Beside each is its reflectance curve, re-plotted on a smaller scale from the curve drawn by the recording spectrophotometer. Notice carefully that each sample reflects to some extent throughout the spectrum. That is, it is not true that the yellow sample reflects only yellow, the green sample only green, and so on.

Let r_λ represent the reflectance of a sample at a wave length λ , and $F(\lambda)d\lambda$ the radiant flux incident on the sample in this wave length range. The reflected flux in the same wave length range, say $f(\lambda)d\lambda$, is evidently

$$f(\lambda)d\lambda = r_\lambda F(\lambda)d\lambda.$$

The tristimulus values of the reflected light are therefore

$$X = \int_0^\infty \bar{x}r_\lambda F(\lambda)d\lambda, \quad Y = \int_0^\infty \bar{y}r_\lambda F(\lambda)d\lambda, \quad Z = \int_0^\infty \bar{z}r_\lambda F(\lambda)d\lambda. \quad (13.4)$$

The trichromatic coefficients x, y, z , are computed by Eq. (13-3).

Evidently the trichromatic coefficients of the light reflected from a given object depend on the spectral composition $F(\lambda)d\lambda$ of the light by which it is illuminated. In other words, the color of the reflected light depends on the color of the illuminant and is not a unique property of the object. For purposes of standardization, the I. C. I. has recommended that the "colors of objects" be stated in terms of the color of the light reflected by them from one of three standard light sources produced by a specified arrangement of incandescent lamps and selectively absorbing solutions. The spectral distributions of these sources, which are designated as illuminants A, B , and C respectively, approximate closely to those of a blackbody at temperatures of 2848°K, 4800°K, and 6500°K. Illuminant C is a good approximation to average daylight, and illuminant A to the light from an incandescent tungsten lamp.

The points representing the chromaticities of the samples in Fig. 13-8, when illuminated by illuminant C , have been plotted in a chromaticity diagram beside each sample. If another illuminant had been used, the coefficients, and the position of the plotted point, would of course have been different.

13-6 Dominant wave length and purity. When two colors are mixed additively, the point representing the chromaticity of the mixture lies on a straight line connecting the points that represent the chromaticities of the components. Thus all additive mixtures of the colors represented by points *D* and *E* in Fig. 13-9 lie somewhere on the line *DE*. If each component is assigned a weight proportional to the sum of its tristimulus values, the point representing the chromaticity of the mixture lies at the center of gravity of these weights. In other words, the greater the proportion of, say, component *D*, the closer to point *D* lies the point representing the mixture. This property of the chromaticity diagram makes possible another means of specifying a color.

A word should first be said about "white" light. There is no unique definition of white light, or, more technically, of *achromatic* light. Average daylight, sunlight, and skylight, although their spectral distributions differ widely, may all be considered "white". It has also been suggested that an equal-energy spectrum (point *E*, Fig. 13-5) should be considered "white". In the absence of an accepted definition, let us speak of illuminant *C* (average daylight) as white or achromatic light, and call point *C* in Fig. 13-9 the *white point*.

All colors that could be obtained or matched by a mixture of white light and the spectrum color *G*, in Fig. 13-9, are represented by points on the line *CG*. If the proportion of white light is large, the representative point of the mixture lies close to the white point. As the proportion of the spectrum color *G* in the mixture is increased, the representative

point moves closer to the spectrum locus and the color approaches a pure spectrum color. Quantitatively, the *purity* of any color is defined as the distance of its representative point from the white point, expressed as a percentage of the distance from the white point to the spectrum locus along a straight line from the white point passing through the given point. For example, the distance *CF* in Fig. 13-9 is about 75% of the distance *CG*, and the purity of the color represented by point *F* is about 75%. The purity of any spectrum color is of course 100%, and the purity of white is zero.

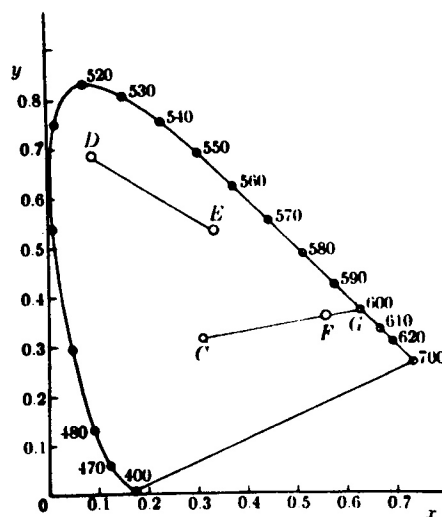


FIG. 13-9.

The *dominant wave length* of a given color is one wave length at which a line from the white point, passing through the point representing the color, intersects the spectrum locus. The dominant wave length of color *F* in Fig. 13-9 is 600 m μ . As stated in Sec. 13-1, the characteristics of dominant wave length and purity, taken together, constitute the *chromaticity* of a given color. The specification of a color in terms of dominant wave length and purity enables the appearance of the color to be visualized more readily than does its description in terms of tristimulus values or trichromatic coefficients.

The dominant wave lengths and purities of the samples in Fig. 13-8 are indicated on their respective chromaticity diagrams.

In the preceding discussion we assumed that the spectral distribution $F(\lambda)$ of the light incident on an object, was expressed in absolute units such as watts per millimicron. In practice, the values of $F(\lambda)$ for illuminants *A*, *B*, and *C* are tabulated in arbitrary units of such magnitude that if the reflectance of a sample, r_λ , is 100% at all wave lengths, ($r_\lambda = \text{constant} = 1$) the integral

$$Y = \int_0^\infty \bar{y} \times 1 \times F(\lambda) d\lambda = 1.$$

Then if the reflectance of any sample is less than unity, the value of Y is decreased in proportion. That is, the value of Y gives, not the luminous flux in the reflected light, but the *average reflectance of the sample* for the particular illuminant to which $F(\lambda)$ applies. The average reflectance is usually expressed as a percentage.

The "color of an object" is understood to include a statement of its average reflectance, together with the dominant wave length and purity of the light it reflects, all with reference to a stated illuminant. For example, the green sample in Fig. 13-8 has an average reflectance of 27.2%, a dominant wave length of 531.5 m μ , and a purity of 34%, all referred to illuminant *C*.

The dominant wave length of a color, although it is not the same thing as the sensation of hue evoked by the color, does correspond to hue in the same way that the wave length of a sound wave corresponds to the sensation of pitch evoked by the wave. Similarly, the purity of a color corresponds to the sensation of saturation and average reflectance corresponds to the sensation of brightness. Chromaticity, which includes the characteristics of dominant wave length and purity, corresponds to chromaticness which includes both hue and saturation.

Mixtures having chromaticities within the triangle *HCJ* in Fig. 13-10

are described as purples or magentas. Since lines from the white point through points in this triangle do not intersect the spectrum locus, purples cannot be matched by a mixture of white and a spectrum color. They are called *non-spectral colors*. The dominant wave length of a purple is obtained by extending a line from its representative point through the white point until it intersects the spectrum locus. The dominant wave length of the color at *K*, in Fig. 13-10, is that of the spectrum color at point *M*. Purple samples reflect more strongly in the red and blue, and less so in the green, and may be described as "minus greens." From the properties of the chromaticity diagram it can be seen that the purple at *K* in Fig. 13-10, and the spectrum color at *M*, could be combined in proper proportions to match illuminant *C*, or white light. When two colors can be added to obtain white they are called *complementary*. The spectrum color at *M* is a green, and is complementary to the purple or minus green at *K*. This is indicated by the suffix *c* following a statement of the wave length of the spectrum color at *M*. (See Fig. 13-8.)

The purity of a color in the region *HCJ* in Fig. 13-10 is defined as the distance of its representative point from the white point, expressed as a percentage of the distance from the white point to the line *HJ* joining the extremities of the spectrum locus. The purity of the color at *K* in Fig. 13-10 is about 25%.

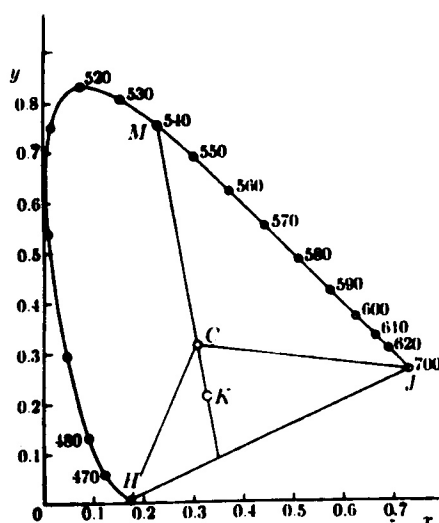


FIG. 13-10. The color at *K* is a purple, complementary to the spectrum color at *M*.

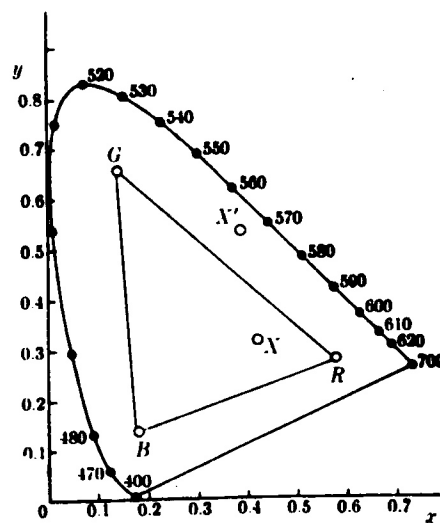


FIG. 13-11. All additive mixtures of components *R*, *G*, *B*, are represented by points within the triangle *RGB*.

Any real color can be considered an additive mixture of spectrum colors. It follows that the representative point of any real color must lie somewhere within the region bounded by the spectrum locus and the straight line joining its extremities. This region is called the *locus of real colors*.

It can now be understood why a wide gamut of colors, but not all colors, can be matched by an additive mixture of three properly chosen (real) components. Suppose the three components are represented by points R , G , and B in Fig. 13-11. All additive mixtures of B and G lie on the line BG . By adding component R to one of these mixtures, any color such as X within the triangle RGB can be matched. A color such as X' could not be matched by mixtures of R , G , and B , but if B were added to X' in such proportions that the mixture were represented by a point on the line RG , this color could then be matched by a mixture of R and G .

It will also be seen that there is no set of real primaries such that the triangle of which they form the corners will include all real colors, but that the widest gamut of colors can be matched if the components are a highly saturated (or a spectrum) red, green, and blue.

The x - and y -coefficients of the standard I. C. I. primaries are, $x = 0$, $y = 0$; $x = 1$, $y = 0$; $x = 0$, $y = 1$. As stated earlier, these points lie outside the realm of real colors, but since the triangle of which they form the corners includes all of the spectrum locus, all real colors can be matched by mixtures of them.

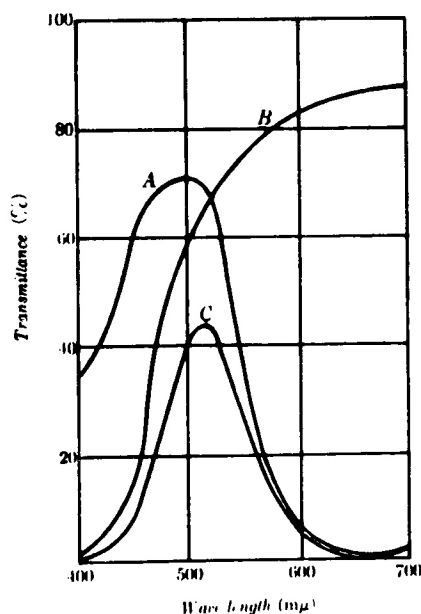


FIG. 13-12. Subtractive color mixing.

13-7 The subtractive method of color mixing. Curves A and B , Fig 13-12, are the transmittance curves of a blue and yellow filter respectively. Suppose the two filters are placed in contact, and inserted in a beam of white light from a projection lantern. We wish to find the color of the transmitted light.

Let the light pass first through the blue and then through the yellow filter. At each wave length, curve A gives the fraction of the

incident light transmitted by the blue filter, and curve *B* gives the *fraction of this fraction* transmitted by the yellow filter. Thus at 500 m μ , 69% of the incident light is transmitted by the blue filter, and 58% of 69%, or 40%, is transmitted by the yellow filter. Hence the transmittance of the combination is found by multiplying the transmittance curves of the filters together, wave length by wave length. The resulting curve is *C*, Fig. 13-12. Evidently the final result is the same if the light passes first through the yellow and then through the blue filter. The transmittance curve has a maximum in the central portion of the spectrum, and the color of the transmitted light will be green. Since each filter subtracts some energy from the light incident upon it, this method of mixing colors is called a *subtractive process*.

13-8 The color of paints and inks. The colors obtained by mixing paints and inks are due to a subtractive process. In the first place, let us consider an opaque white paint or ink. Its base is a liquid "vehicle," usually linseed oil. The vehicle is quite colorless and transparent. Suspended in it are tiny particles of equally colorless and transparent material, such as an oxide of lead, zinc, or titanium. The index of refraction of the suspended material must be as different as possible from that of the vehicle. We have seen that whenever light is incident on a surface bounding two media of different indices of refraction, some of the light is reflected at the surface. Consider a ray striking the surface of the white paint, Fig. 13-13. Some light will be reflected at the air-vehicle surface, since there is a change in index at this surface. The remainder penetrates into the paint and strikes a boundary between vehicle and suspended particle, where again a portion is reflected. The reflected part returns through the surface, and the part remaining penetrates further, a portion being reflected at each boundary surface which it crosses. Since reflection occurs whatever the wave length of the incident light, the paint reflects uniformly throughout the spectrum, or in other words, it is "white." Note that its white "color" is not produced by suspending white particles in the vehicle, but is due simply to a difference in index between particle and vehicle, both of which are transparent.

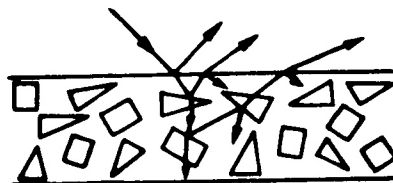


FIG. 13-13.

If a colored paint or ink is desired, the suspended particles are dyed the desired color, or other dyed particles are added to the white paint.